Galactic chemical evolution of Lithium: interplay between stellar sources

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ABSTRACT

In this paper we study the evolution of ^{7}Li in the Galaxy considering the contributions of various stellar sources: type II supernovae, novae, red giant stars, and asymptotic giant branch (AGB) stars. We present new results for the production of ^{7}Li in AGB stars via the hot bottom burning process, based on stellar evolutionary models by Frost (1997). In the light of recent observations of dense circumstellar shells around evolved stars in the Galaxy and in the Magellanic Clouds, we also consider the impact of a very high mass-loss rate episode (superwind) before the evolution off the AGB phase on the ^{7}Li enrichment in the interstellar medium. We compare the Galactic evolution of ^{7}Li obtained with these new ^{7}Li yields (complemented with a critical re-analysis of the role of supernovae, novae and giant stars) with a selected compilation of spectroscopic observations including halo and disk field stars as well as young stellar clusters.

We conclude that even allowing for the large uncertainties in the theoretical calculation of mass-loss rates at the end of the AGB phase, the superwind phase has a significant effect on the ^{7}Li enrichment of the Galaxy.

Subject headings: nucleosynthesis - stars: abundances, AGB and post-AGB - Galaxy: evolution, abundances

1. Introduction

In spite of many attempts, the evolution of ^{7}Li in the Galaxy is not completely understood. Lithium has the unique property of being produced by, at least, three different processes: Big Bang nucleosynthesis, spallation of Galactic cosmic-ray (GCR) particles on interstellar matter (ISM) nuclei, and stellar nucleosynthesis. At the same time, ^{7}Li is easily destroyed by proton captures in stellar interiors at relatively low temperatures ($\sim 2.5 \times 10^6$ K).

Observationally, Population I (hereafter Pop. I) dwarf stars show a large dispersion in ^{7}Li abundance attributed to different amounts of depletion. On the contrary the abundance of ^{7}Li in the atmosphere of old, warm ($T_{\rm eff} > 5700$ K) Population II (hereafter Pop. II) dwarf stars is surprisingly uniform: $^7{\rm Li/H} \simeq 1.1 \times 10^{-10}$ (Spite & Spite 1982), a value ~ 10 times lower than the maximum abundance observed in Pop. I stars. Several studies have subsequently confirmed the existence of the so-called "Spite plateau" in Pop. II stars, although discrepancies on the actual value of the plateau still exist at the level of ~ 0.1 dex (see e.g., Spite & Spite 1986; Hobbs & Duncan 1987; Rebolo, Beckman, & Molaro 1988; Thorburn 1994; Spite et al. 1996; Bonifacio & Molaro 1997) [1].

There is an ongoing debate about whether the Spite plateau corresponds to the (almost) undepleted primordial abundance of ^{7}Li , or whether the primordial value is closer to $\log \epsilon(^7{\rm Li}) \simeq 3.1$–$3.3$ (the value measured in the youngest stars and solar system meteorites) and has been significantly but uniformly depleted in Pop. II stars (see e.g. Deliyannis & Ryan 1997; Bonifacio & Molaro 1997). On one hand, the former interpretation requires processes that increase the Galactic ^{7}Li abundance by a factor ~ 10 in the first few Gyr. On the other hand *standard models* of stellar evolution which incorporate only convective mixing predict little (~ 0.1 dex) ^{7}Li depletion in Pop. II stars (e.g., Deliyannis, Demarque & Kawaler 1990). Stellar models including the effects of non-standard processes (like e.g. diffusion, winds, turbulence induced by rotational instabilities, slow mixing driven by angular momentum loss,

[1] In this paper we adopt the usual notation $\log \epsilon(^7{\rm Li}) = \log[N(^7{\rm Li})/N({\rm H})] + 12$. The Spite plateau corresponds to $\log \epsilon(^7{\rm Li}) \simeq 2.1$.

etc.) predict substantial ^{7}Li destruction in Pop. II stars (see Pinsonneault 1997 for a review). These non-standard models predict observable features, like a dispersion in ^{7}Li among halo dwarfs, or correlations between ^{7}Li and $T_{\rm eff}$ or [Fe/H], which have not been confirmed by observations, suggesting that ^{7}Li destruction must have been minimal in these stars (see e.g., Boesgaard & Steigman 1985, Bonifacio & Molaro 1997, Ryan, Norris, & Beers 1999, Ryan et al. 2000). It is true, however, that the presence of a few metal–poor stars with ^{7}Li abundances somewhat above the plateau, as well as other observational evidences in Pop. I stars (Deliyannis et al. 1998, Deliyannis 2000) support the idea that halo dwarfs may have suffered a certain amount of ^{7}Li depletion.

Indication of a primordial abundance of ^{7}Li in excess of the Spite plateau value is suggested also by (*i*) recent determinations of deuterium abundances in Lyman-α clouds (see e.g. Pettini & Bowen 2001 and references therein), and (*ii*) observations of the spectrum of fluctuations in the cosmic background radiation (de Bernardis et. al. 2000, Tegmark & Zaldarriaga 2000). In both cases the value of the baryon-to-photon ratio η_{10} results in the range 6–7, rather than 4–5 as usually assumed. This implies a cosmological abundance of ^{7}Li in excess of the Spite plateau value by a factor 2–3, still compatible with the observationally allowed range of primordial ^{4}He. However, one should be very careful in interpreting these indications since possible sources of systematic errors have still to be completely understood and eliminated from the observational data. The issue remains therefore open.

Assuming that the Spite plateau corresponds to the primordial ^{7}Li abundance, the difference between the plateau abundance and the maximum ^{7}Li content in Pop. I stars underscores the need for one or more sites of ^{7}Li production.

It is well known that ^{9}Be, ^{10,11}B, and ^{6,7}Li can be produced via spallation and fusion reactions between GCR particles and ISM nuclei (Fowler, Reeves, & Silk 1970; Meneguzzi, Audouze & Reeves 1971). Whereas theoretical calculations of the amounts of ^{9}Be, ^{10,11}B and ^{6}Li produced by GCR (see e.g. Lemoine, Vangioni-Flam, & Cassé 1998; Fields & Olive 1999; Ramaty et al. 2000, and references therein) can roughly reproduce the observed values, the amount of ^{7}Li produced by spallation processes at the time of formation of the Sun is a factor 5–10 lower than the measured meteoritic value (see also Nissen et al. 1999 and references therein)[2].

Additional sites of ^{7}Li production are therefore required to match the observational

[2]At lower metallicity, in particular in the range $-2 <$ [Fe/H] < -0.5, the predictions of GCR spallation models indicate a possible overproduction of ^{6,7}Li due to α-α reactions (Prantzos et al. 1993, Valle et al. 2001 in preparation) that may suggest the occurence of a depletion process in halo stars at least in this metallicity range.

data. For example, D'Antona & Matteucci (1991) proposed that novae and AGB stars may represent the main sources of Galactic ^{7}Li , whereas Matteucci, D'Antona, & Timmes (1995) favoured a model where the main contributors to ^{7}Li enrichment are SNII and AGB stars. Abia, Isern, & Canal (1995) considered the production of ^{7}Li by low-mass AGB stars, whereas Romano et al. (1999) showed that novae are required in order to reproduce the growth of ^{7}Li with metallicity, and that the contribution from SNII should be lowered by at least a factor of two. Finally, Romano et al. (2001), using recent AGB models by Ventura, D'Antona, & Mazzitelli (2000), concluded that AGB stars are not substantial ^{7}Li producers in the Galaxy.

In this paper we reanalyze the problem afresh with the help of a numerical model of Galactic chemical evolution and a set of new models of AGB stars of various masses and metallicities. We consider various stellar sources of ^{7}Li : novae, type II supernovae, low– and intermediate–mass stars in the red giant branch (RGB) and AGB phase. All these sources can produce ^{7}Li , as shown by theoretical models, and, in some cases, also confirmed by spectroscopic data. However, individual ^{7}Li yields are rather uncertain and strongly dependent on model parameters and assumptions.

The paper is organized as follows. In § 2 we discuss our sample of observational data for field stars and open clusters. In § 3 we briefly describe the adopted model for Galactic chemical evolution. In the following Sections we then focus on the analysis of the ^{7}Li production by different stellar sources. In particular in § 4 we consider the role of intermediate-mass AGB stars (hereafter IMS-AGB), presenting new ^{7}Li yields obtained from the AGB models by Frost (1997). We reanalyze the production of ^{7}Li by novae (§ 5), SNII (§ 6), and low-mass RGB stars (§ 7), on the basis of recent model calculations and observations. Finally, in § 8 we discuss and summarize our results.

2. Observational data

2.1. ^{7}Li abundances in field dwarfs

The main source of our compilation is the recent study by Fulbright (2000) who determined ^{7}Li , Fe, and other element abundances for 168 halo and disk stars. Both stellar parameters and abundances of ^{7}Li and Fe were inferred by carrying out a self-consistent LTE analysis, providing a homogeneous sample of both Pop. II and Pop. I stars. The survey of Fulbright does not extend to very low or very high metallicities; therefore we complemented it for [Fe/H] < -2 with the compilation of Bonifacio & Molaro (1997). At [Fe/H] > -0.4 we included a sample of warm ($T_{\rm eff} \geq 5700$ K), unevolved F-type stars taken from Balachan-

dran (1990) and Lambert, Health, & Edvardsson (1991). We note that, whereas cooler stars have certainly undergone Li depletion (unless very young), considering only stars warmer than 5700 K allows having a subsample of minimally depleted stars which trace the upper envelope of the ^{7}Li vs. [Fe/H] distribution. Surveys of ^{7}Li among Pop. II stars have also been made by e.g. Rebolo et al. (1988), Thorburn (1994), Ryan, Norris, & Beers (1996), Spite et al. (1996), Ryan et al. (2001). Different datasets and/or analysis methods (in particular the use of different effective temperature calibrations) lead in general to a different abundance scale: therefore, including ^{7}Li abundances from many different sources in the same compilation may introduce a spurious (i.e. not real) dispersion in the ^{7}Li vs [Fe/H] distribution. For this reason, we decided to base our compilation of ^{7}Li abundances for Pop. II stars on the minimum number of studies allowing the full coverage of the entire metallicity range. We mention that Fulbright (2000) derived an average offset between his and Bonifacio & Molaro's (1997) effective temperatures $\Delta T_{\rm eff} = -38 \pm 20$ K, which should not introduce major systematic differences in the inferred ^{7}Li abundances. There are several stars in common between the two studies: for all of them the agreement in ^{7}Li abundances is indeed very good (within ~ 0.1 dex).

We did not include in our list stars evolved off the main sequence (hereafter MS) and/or stars cooler than 5700 K; both groups of stars most likely did not preserve their original ^{7}Li content due to either post-MS dilution or to MS ^{7}Li depletion and thus are not adequate to trace the upper envelope of the ^{7}Li vs. metallicity distribution. We also did not include ^{7}Li abundances for T Tauri stars, since they may be affected by several problems such as spectral veiling, NLTE, or, more generally, by the effects of a "disturbed stellar photosphere" (see e.g. Duncan 1991). Instead, we included in our compilation the average abundance of warm (i.e. F–type) stars in young open clusters with $-0.1 <$[Fe/H]< 0.1. These stars have undergone minimal pre-MS or MS ^{7}Li depletion and thus their abundance can be considered as representative of the present ISM ^{7}Li content. Several surveys of ^{7}Li among open cluster stars (see e.g. Jeffries 2000 for a recent review) have shown that Li-undepleted stars in all the investigated clusters share the same abundance $\log\epsilon(^7\mathrm{Li}) = 3.2 \pm 0.1$ (e.g., Randich et al. 1997)[3].

In the upper panel of Figure 1 we plot the ^{7}Li abundance vs. metallicity for the stars of our sample. A few features in this figure warrant detailed comments. As far as the ^{7}Li plateau is concerned, recent studies have inferred slightly different values for the plateau

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[3]Although ^{7}Li abundances as high as $\log\epsilon(^7\mathrm{Li}) = 4$ have been derived for some T Tauri stars, Magazzù, Rebolo, & Pavlenko (1992) and Martín et al. (1994) concluded that abundances of pre-MS stars (including both classical and weak-lines T Tauri stars) as a whole indicate an initial ^{7}Li abundance for Pop. I stars $\log\epsilon(^7\mathrm{Li}) = 3.1$.

value, due – as mentioned above – to different types of analysis and, in particular, to possible offsets in the zero-point of the effective temperature scale (see e.g., Spite et al. 1996). In our model of Galactic evolution we have generally adopted as initial ^{7}Li abundance the value determined by Bonifacio & Molaro (1997) for the Spite plateau, i.e. $\log\epsilon(^7\mathrm{Li})_0 = 2.24 \pm 0.012$, under the implicit assumption that the Spite plateau represents the primordial (Big-Bang) abundance. We mention in passing that the mean abundance of the stars in the compilation of Fulbright (2000) with [Fe/H]≤ -1 is $\log\epsilon(^7\mathrm{Li})_0 = 2.24 \pm 0.095$ in excellent agreement with the estimate of Bonifacio & Molaro (1997). We also ran our model starting with an initial ^{7}Li abundance higher by a factor 2 than the Spite plateau value (see below), following the idea that Pop. II stars may have depleted a certain amount of Li in the course of their evolution.

Figure 1 also suggests that the rise of ^{7}Li abundance from the Spite plateau may be smoother than claimed in previous studies. In particular, a few stars are present in the survey of Fulbright (2000) which have intermediate metallicities ($-0.7 \leq$ [Fe/H] ≤ -0.45) and ^{7}Li abundances 0.2–0.3 dex (i.e. $> 1\sigma$) above the plateau but not as high as $\log\epsilon(^7\mathrm{Li}) \simeq 3$. However, the caveat is that only a few stars define the upper envelope at intermediate metallicity and we cannot exclude that these stars have suffered some Li depletion.

A sharp increase to abundances as high as the present ISM abundance may occur at metallicities between [Fe/H]$= -0.45$ and -0.35, if the abundances for the few stars which trace the upper envelope of the distribution at those metallicities are correct. These stars are from the survey of Balachandran (1990), but we mention that Li abundances derived by Balachandran are systematically higher than those of Boesgaard & Tripicco (1986), with differences in the range 0.2 – 0.6 dex. For the case of HR 8315 (HD 206901) Lèbre et al. (1999) inferred a metallicity [Fe/H]$= -0.3$ and a ^{7}Li abundance $\log\epsilon(\mathrm{Li}) = 2.9$ to be compared with [Fe/H]$= -0.37$ and $\log\epsilon(\mathrm{Li}) = 3.05$ determined by Balachandran (1990). We also notice that photometric iron abundances for some of the intermediate metallicity and Li-rich stars observed by Balachandran (1990) are at least 0.2 dex higher than the spectroscopic values inferred by Balachandran (see the last two columns of Table 1 in Balachandran 1990), suggesting again that ^{7}Li abundance ~ 3 is reached only at higher metallicities (i.e. [Fe/H]≥ -0.3). Determinations of ^{7}Li abundances in this critical metallicity range are certainly needed in order to better constrain the ^{7}Li vs. [Fe/H] upper envelope.

2.2. ^{7}Li abundances in clusters

In the lower panel of Figure 1 we show the abundance of ^{7}Li vs. Galactic age using ^{7}Li data for stars in Galactic open and globular clusters. We also show the meteoritic

^{7}Li abundance ($\log \epsilon(^7\text{Li}) = 3.31 \pm 0.04$, Anders & Grevesse 1989), the interstellar ^{7}Li abundances determined in the line-of-sight toward ρ Oph (^{7}Li /H $\gtrsim 2.4 \times 10^{-10}$, Lemoine et al. 1993), and toward o and ζ Per (^{7}Li /H $= (9.8 \pm 3.5) \times 10^{-10}$ and $(12.2 \pm 2.2) \times 10^{-10}$, Knauth et al. 2000). For young open clusters (ages < 1 Gyr) the average abundance measured in warm ($T_{\rm eff} \geq 6000$ K), undepleted cluster MS stars, is plotted in the Figure. The data were taken from the following sources: Soderblom et al. (1999) for NGC 2264; Randich et al. (1997) for IC 2602; Randich et al. (2001) for IC 2391; Martín & Montes (1997) for IC 4665; Randich et al. (1998) for Alpha Persei; Soderblom et al. (1993) for the Pleiades; Thorburn et al. (1993) for the Hyades. On the other hand, the initial abundance for older clusters was estimated from stars at (or just evolved off) the turn-off in the 2 Gyr clusters NGC 752 (Hobbs & Pilachowski 1986), NGC 3680 (Randich, Pasquini, & Pallavicini 2000) and from the abundances of the two components of the tidally locked binary S1045 in the solar-aged M 67 cluster (Deliyannis et al. 1994; Pasquini, Randich, & Pallavicini 1997). Finally, globular clusters (GCs) are represented by a box that shows the ranges in ^{7}Li and age estimates. More specifically, GCs absolute ages are the subject of a long standing debate; in the lower panel of Figure 1 we used the recent determination by Carretta et al. (2000), who inferred an average age of 12.9 ± 2.9 Gyr based on *Hipparcos* parallaxes for local subdwarfs. We mention, however, that ages as large as 16–17 Gyr cannot be ruled out.

Abundances of ^{7}Li were derived for unevolved stars at the turn-off in three clusters only, namely, NGC 6397 (Pasquini & Molaro 1996), 47 Tuc (Pasquini & Molaro 1997), and M 92 (Boesgaard et al. 1998); whereas the average abundances for the three clusters are close to the value of the Spite plateau, stars in the same cluster show a significant dispersion in ^{7}Li (see discussion in Boesgaard et al. 1998) and, in particular, a star is found in M 92 with a ^{7}Li content significantly higher than the plateau and the other cluster stars. Consequently, we think that the use of a box is more appropriate to indicate the position of GCs in Figure 1.

3. The Galactic chemical evolution model

The model of Galactic chemical evolution adopted in this work is described in detail by Ferrini & Galli (1988), Galli & Ferrini (1989) and Ferrini et al. (1992). The same model was adopted by Galli et al. (1995), Travaglio et al. (1999) and Travaglio et al. (2001), to study the evolution of the light elements D and ^{3}He, and the evolution of the heavy elements from Ba to Pb, respectively. We briefly recall here the basic features of the model.

The Galaxy is divided into three zones, halo, thick disk, and thin disk, whose composition of stars, gas (atomic and molecular) and stellar remnants is computed as functions of time up to the present epoch $t_{\rm Gal} = 13$ Gyr. The thin disk is formed from material infalling

from the thick disk and the halo. The formation of the Sun in the thin disk takes place 4.5 Gyr ago, i.e. at epoch $t_\odot = 8.5$ Gyr. The star formation rate in the three zones is not assumed *a priori*, but is obtained as the result of self-regulating processes occurring in the molecular gas phase, either spontaneously or stimulated by the presence of other stars.

In models of Galactic chemical evolution it is customary to separate the contribution of stars in different mass ranges to the enrichment of the ISM. Our model follows the evolution of (*i*) single low- and intermediate-mass stars ($0.8\ M_\odot \leq M \leq M_\star$) ending their life as He or C-O white dwarf, (*ii*) binary systems able to produce type I supernovae, and (*iii*) single massive stars ($M_\star \leq M \leq 100\ M_\odot$), the progenitors of type II supernovae. The value of $M_\star$ depends on metallicity; we assume $M_\star = 6\ M_\odot$ for [Fe/H]≤ -0.8, and $M_\star = 8\ M_\odot$ otherwise (see for references Tornambè & Chieffi 1986). The adopted initial mass function (hereafter IMF) is discussed in Ferrini et al. (1992). Stellar nucleosynthesis is treated according to the matrix formalism introduced by Talbot & Arnett (1973). Specific yields are taken from calculations by Woosley & Weaver (1995) and Thielemann, Nomoto, & Hashimoto (1996), for type II and type I supernovae, respectively.

4. The production of ^{7}Li by hot bottom burning process

Hot bottom burning (hereafter HBB) occurs in intermediate mass AGB stars when the bottom of the convective envelope of the star reaches the top layers of the hydrogen burning shell. Sackmann & Boothroyd (1992) showed that the Cameron-Fowler mechanism (Cameron 1955; Cameron & Fowler 1971) is very effective at producing ^{7}Li , and can quantitatively account for the ^{7}Li abundance measured by Smith & Lambert (1990) in the super-Li rich AGB stars in the Magellanic Clouds. We present here a summary of results for ^{7}Li production in AGB stars of various masses and metallicities, based on the evolutionary models of Frost (1997) and synthetic models using the technique of Forestini & Charbonnel (1997). We then discuss the sensitivity of ^{7}Li enrichment to the mass-loss prescriptions during the latest phases of AGB evolution.

4.1. Li production from 4, 5, 6 $M_\odot$ AGB models at different metallicities

Frost (1997) computed the evolution of 4, 5, and 6 $M_\odot$ models each with metal content $Z = 0.02$, 0.008, and 0.004, appropriate to the solar neighborhood, and to the Large and Small Magellanic Clouds, spanning the evolution from the MS through the end of the AGB phase. Each case has been the subject of a detailed nucleosynthesis study using a modified

post-processing code (Cannon 1993) including 74 species and over 500 reactions. Some of the results of these models have been already published (e.g. Frost et al. 1998, Lattanzio & Forestini 1999); in this paper we present in detail an analysis of the production of ^{7}Li.

Our present approach is to use the stellar models of Frost (1997) as the basis of synthetic models computed with the code of Forestini & Charbonnel (1997). In this way we force the synthetic code to follow the results of the stellar models (accuracy is within 10%), yet we are free to vary those parameters which have no significant feedback on the evolution. In particular, for the aim of this paper, we investigated the mass-loss rate at the end of the AGB phase (see next Section for detailed discussion). We do not expect modest changes in the mass-loss rate during the latest AGB phase to have a significant effect on the structural evolution of the star, since the variations in the mass-loss rate only affect the very late phases of stellar evolution. Nevertheless, we caution against placing too much belief in the quantitative results for the extreme cases discussed below.

The surface ^{7}Li abundances during the AGB lifetime in the stellar envelope for the nine models considered here is presented in Figure 2. Note that the abundance of ^{7}Li at the beginning of the AGB phase varies from one model to another as a result of previous evolution. Fig. 2 is a 3×3 grid figure with mass increasing along the x-axis and Z decreasing along the y-axis: in this way we expect HBB to increase for increasing x-axis (mass) or increasing y-axis (decreasing Z). The most extreme HBB is for the top right plot, i.e. $M = 6\ M_\odot$ model with $Z = 0.004$, where the maximum ^{7}Li production lasts for the longest time ($\sim 10^5$ yr). The maximum ^{7}Li abundances we obtain range around $\log\epsilon(^7\mathrm{Li}) \simeq 4$, independent of stellar mass and metallicity, and only depending on the occurrence of HBB. The models with $M = 4\ M_\odot$ and $Z = 0.02$, 0.008 show no HBB and consequently no ^{7}Li production. In fact, ^{7}Li destruction in these two models proves that their convective bottom temperatures are high enough to burn ^{7}Li through $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$ channel, but not enough to produce ^{7}Be (that decays to ^{7}Li, Cameron-Fowler mechanism) by ^{3}He burning. Conversely the 6 $M_\odot$ models, with their substantial envelopes, begin HBB immediately on the AGB and hence they produce a large amount of ^{7}Li , but the high envelope temperature also assists in the destruction of ^{7}Li . Finally, Figure 2 shows that in all models, as the evolution of the star proceeds, the surface ^{7}Li abundance decreases again more or less rapidly, depending on the mass and metallicity. This indicates that the initial reserves of ^{3}He have been consumed in the production of ^{7}Li , and this ^{7}Li is now itself being destroyed (without replenishment) by proton captures.

There are observational indications that some Galactic C-stars (stars with C/O > 1) are also super-Li rich stars ($\log\epsilon(^7\mathrm{Li}) \geq 3$, see e.g. Abia et al. 1991, Abia, Pavlenko, & de Laverny 1999, Abia & Isern 2000). Therefore, we also examined the ^{7}Li vs. C/O trends

for the nine cases presented above. The models of Frost (1997) use the algorithm for the third dredge-up (i.e. the penetration of the convective envelope into the partially He-burnt zone after each thermal pulse), as described by Frost & Lattanzio (1996), and include the entropy adjustment by Wood (1981). After each third dredge-up episode the ^{12}C abundance is increased. Hence third dredge-up increases the ratio C/O (by adding C to the stellar envelope), and HBB (where it is active) decreases it again as it transforms C into N. Figure 3 shows the C/O ratio vs. ^{7}Li for the nine models under consideration. In some cases HBB prevents the formation of a C star, while in other cases it merely delays the formation to a time when HBB has stopped and third dredge-up continues (see Frost et al. 1998 for more details). The condition C/O $>$ 1 together with high ^{7}Li values are obtained only for the case $Z = 0.004$ and $M = 4\ M_{\odot}$ and for a very short phase for the case with the same metallicities and $M = 5\ M_{\odot}$. In particular, the 4 $M_{\odot}$ model is a Li-rich star (with $\log \epsilon(^{7}\mathrm{Li}) \sim 4$) and C-rich star for a period of about 10^5 yr. Moreover, all the other cases show high ^{7}Li abundances together with O-rich envelopes, in agreement with observations of AGB stars in the Magellanic Clouds (see e.g. Smith et al. 1995) and in the Galaxy (see e.g. the recent work from Arellano Ferro, Giridhar, & Mathias 2001).

The range of $M_{\rm bol}$ covered by the nine models presented here ($-7 \leq M_{\rm bol} \leq -6$) during the Li-rich phase is in agreement with bolometric magnitudes of the super-Li rich stars observed in the Magellanic Clouds (Smith et al. 1995). Concerning Galactic super-Li rich C stars, only few estimates of their $M_{\rm bol}$ are available. Abia et al. (1991), based on the distance determinations by Claussen et al. (1987), estimated $M_{\rm bol} \simeq -5$ for WZCas and WXCyg (with $\log \epsilon(^{7}\mathrm{Li}) = 5.0$ and 4.7, respectively). More recently, Abia & Isern (2000), based on *Hipparcos* parallaxes, inferred $M_{\rm bol} = -6.44$ and $\log \epsilon(^{7}\mathrm{Li}) = 4.8$ for WZCas, and $M_{\rm bol} = -4.35$ and $\log \epsilon(^{7}\mathrm{Li}) = 4.4$ for WXCyg. However, a caveat is that the latter is based on a parallax $\pi = -1.41 \pm 1.98$, which is unreliable. Two additional Galactic C-rich super-Li rich stars have been presented by Abia et al. (1991): IYHya ($M_{\rm bol} = -6.2$ and $\log \epsilon(^{7}\mathrm{Li}) = 5.4$), and TSgr ($M_{\rm bol} = -5.8$ and $\log \epsilon(^{7}\mathrm{Li}) = 4.2$). Given the uncertainties, and excluding the not reliable measurement of $M_{\rm bol}$ for WZCas by Abia & Isern (2000), we conclude that the $M_{\rm bol}$ determinations for the Galactic super-Li rich stars are still consistent with the $M_{\rm bol}$ reached by our AGB models during the super-Li rich phase. We also notice that the highest abundance reached by our models for $\log \epsilon(^{7}\mathrm{Li})$ is ~ 4, while higher values are inferred from observations.

4.2. Superwind in AGB stars: consequences for Li chemical enrichment

There are observational indications that toward the end of their evolution, AGB stars (both of low- and intermediate-mass) can experience a short phase of extremely rapid mass-loss, called *superwind* (van der Veen, Habing, & Geballe 1989; Schröder, Winters, & Sedlmayr 1999). In this phase periods of heavy mass-loss may be interspersed with much longer periods of lower mass-loss rates, possibly powered by He shell flashes. These stars are often surrounded by a dense circumstellar envelope and some of them are no longer visible at optical wavelengths. Evidence for a superwind has been found in CO observations of C stars (e.g. Olofsson 1993), of K giants (de La Reza et al. 1997; Castilho et al. 1998), and in post-AGB objects that show concentric rings around the central object (see e.g. Crabtree & Rogers 1993; Latter et al. 1993; Riera et al. 1995; Klochkova et al. 1999; Blöcker et al. 2001).

From the theoretical point of view, the term of superwind has been coined (Renzini 1981) to describe the heavy, final tip-AGB mass-loss ($\geq 10^{-5}$ $M_\odot$ yr^{-1}), which is required to form a planetary nebula of typically tenths of a solar mass within several 10^4 yr. The idea of a star terminating its AGB life with a superwind has been also elaborated by Bowen & Willson (1991). These authors showed that all stars undergo the superwind phase as a result of an increase in scale height and density at the condensation radius as the star evolves toward the tip of the AGB. Analytical expressions to describe this phase of high mass-loss have been presented by different authors, e.g. by Vassiliadis & Wood (1993, hereafter VW93), Blöcker (1995), Salasnich, Bressan, & Chiosi (1999). VW93 computed the effects of thermal pulses on mass-loss rates and suggested that a star may undergo several superwind phases and that more massive stars will stay longer in the superwind phase than lower mass stars. For the AGB models discussed in this Section the superwind prescription follows the formula of VW93 (without the correction for masses above 2.5 $M_\odot$)

$$\log\left(\frac{dM}{dt}\right) = -11.4 + 0.0125P, \tag{1}$$

where the mass-loss rate is in $M_\odot$ yr^{-1} and P is the pulsation period in days. Note that the mass-loss rate is truncated at

$$\frac{dM}{dt} = \frac{L}{cv_{\rm exp}}, \tag{2}$$

where L is the stellar luminosity, corresponding to a radiation-pressure driven wind. Again from VW93 we take the wind expansion velocity (in km s^{-1})

$$v_{\rm exp} = -13.5 + 0.056P, \tag{3}$$

ranging between 3.0 and 15.0 km s^{-1}.

The ^{7}Li yields are very sensitive not only on the extent of the HBB, but also on the mass-loss rate prescriptions. As first qualitatively pointed by Abia, Isen, & Canal (1993), it is not clear if during the super-Li rich phase AGB stars are able to inject ^{7}Li into the interstellar medium by the high mass-loss rate before ^{7}Li is depleted in the atmosphere. We analyze this point with our models, and we plot in Figure 4 the surface ^{7}Li abundance as a function of the mass-loss rate for the nine models described in the previous Section. The figure shows that only in a few cases does the star achieve very high mass-loss rates ($> 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$) when the surface ^{7}Li abundances is still high ($\log\epsilon(^7\mathrm{Li}) > 3$). When this happens the overall ^{7}Li yield is positive, or only slightly negative. In the first three columns of Table 1 we report the ^{7}Li yields (in $M_\odot$) obtained with these models, showing that only in the case of 4 $M_\odot$ and $Z = 0.004$ the ^{7}Li yield is positive.

Another way to investigate the sensitivity of ^{7}Li yields to the choice of the mass-loss rate is shown in Figure 5, where we plot the surface ^{7}Li abundance as a function of the total stellar mass (so that the models evolve from right to left). Note that for the models with $Z = 0.02$ we assumed an initial (i.e. at the time when the star formed) $\log\epsilon(^7\mathrm{Li}) \simeq 3.3$, compatible with the meteoritic abundance; this value scales with Z for the other metallicities. In order to get a positive yield of ^{7}Li the star's mass should decrease substantially while $\log\epsilon(^7\mathrm{Li}) > 3$–4. Hence, although the 5 and 6 $M_\odot$ models experience HBB, the 5 $M_\odot$ loses about 1 $M_\odot$ when $\log\epsilon(^7\mathrm{Li}) \simeq 4$, whereas the 6 $M_\odot$ loses most of its mass when $\log\epsilon(^7\mathrm{Li})$ is 3.5 or lower. Hence the yield from 5 $M_\odot$ model, although still negative, is smaller in its absolute value than the 6 $M_\odot$ model. That is, the 5 $M_\odot$ model does not destroy as much ^{7}Li as the 6 $M_\odot$ model, due to the large amount it returns to the ISM, although the overall yield is still negative, with respect to the initial abundance. At a lower value of Z (~ 0.008) where typical interior temperatures are higher, both the 5 $M_\odot$ and 6 $M_\odot$ models clearly show HBB, and there is a small amount of HBB at 4 $M_\odot$, although $\log\epsilon(^7\mathrm{Li})$ never exceeds 2. Again, most of the mass-

TABLE 1
^{7}Li yields (in solar masses) from intermediate-mass AGB stars

	(*a*)			(*b*)		
	$Z = 0.004$	$Z = 0.008$	$Z = 0.02$	$Z = 0.004$	$Z = 0.008$	$Z = 0.02$
4 $M_\odot$	1.1×10^{-8}	-1.7×10^{-8}	-4.3×10^{-8}	1.5×10^{-8}	-1.3×10^{-8}	-3.3×10^{-8}
5 $M_\odot$	-1.1×10^{-8}	-1.9×10^{-8}	-4.0×10^{-9}	4.5×10^{-8}	7.3×10^{-8}	2.2×10^{-8}
6 $M_\odot$	-1.3×10^{-8}	-2.5×10^{-8}	-1.3×10^{-8}	4.1×10^{-8}	7.2×10^{-8}	7.7×10^{-8}

(*a*) Mass-loss rate from VW93
(*b*) Mass-loss rate from VW93 increased by a factor 50

loss for these models occurs when the surface $\epsilon(^7\mathrm{Li})$ is less than the initial value, and hence the overall yields are negative (see Table 1). Finally, at $Z = 0.004$ the higher temperature means that there is significant ^{7}Li production even at 4 $M_\odot$. This is particularly strong in the more massive models, but this does not correspond to a positive ^{7}Li yield because the ^{7}Li is destroyed before the high mass-loss begins. In contrast, the 4 $M_\odot$ model has its HBB delayed, and toward the end of its evolution the increased mass-loss begins when the surface ^{7}Li is higher, and hence the overall yield is higher. Also note that the high values found for $\log\epsilon(^7\mathrm{Li})$ in the 5 and 6 $M_\odot$ models do not last until the mass-loss reaches appreciable values. By the time that the mass-loss begins in earnest, the surface ^{7}Li abundance is below the initial value. For the 4 $M_\odot$ case, however, there is about a half solar mass of material lost when $\log\epsilon(^7\mathrm{Li})$ is above 3. A conclusion from these results is that the higher ^{7}Li yields come from the lower mass stars: in fact, from those stars which just start HBB when the high mass-loss rate begins.

Due to the fact that ^{7}Li yields are very sensitive to the mass-loss choices, we have run each of the models presented above using different mass-loss rates. Since several observations of OH/IR stars (i.e. O-rich AGB stars that exhibit OH masers, Wilson & Barrett 1972) with infrared excesses (i.e. high mass-loss rates, see e.g. Blöcker et al. 2001) and $P \sim 400$–500 days are now available (see e.g. Lewis 2000 for a recent survey of OH/IR IRAS sources), we forced the mass-loss to start at shorter periods. In order to obtain $dM/dt \geq 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$ with $P \simeq 500$ days the VW93 prescription has to be increased of a factor of ~ 50. In Table 1 (columns 5, 6, 7) we list the yields obtained with this modification to the VW93 prescription. The surface ^{7}Li abundance for the different models vs. stellar mass is also shown in Figure 5 for comparison. Both the table and the figure indicate that, when using this mass-loss rate prescription, the ^{7}Li yields for most of the cases are positive.

The chemical evolution model described in § 3 has been run using the Li yields given in Table 1 (first three columns): we obtain that intermediate-mass AGB stars contribute to the solar system ^{7}Li abundance for $\sim 14\%$. Under these conditions, IMS-AGB stars can contribute only a small fraction to the ^{7}Li solar composition and they do not seem able to reproduce the rapid increase of ^{7}Li in the Galactic disk. When we introduce in the GCE model the ^{7}Li yields obtained the modified VW93 mass-loss prescription (Table 1, last three columns) and we find that the contribution of intermediate-mass AGB stars to the solar ^{7}Li composition increases by a few percent ($\sim 6\%$). In Figure 6 (*upper panel*) we compare the observed $\log\epsilon(^7\mathrm{Li})$ vs [Fe/H] distribution with the predictions of the model including the modified VW93 mass-loss prescription.

We also notice that we limited the IMS-AGB upper mass to 6 $M_\odot$. This is due to the fact that we did not yet run models for 7 and 8 $M_\odot$ AGB stars.. Nevertheless we extrapolate

the 6 $M_\odot$ yields to 7 and 8 $M_\odot$ models to test the 4–8 $M_\odot$ IMS-AGB mass range. We found that the results change only by few percent, due to the lower weight on the IMF of the 7 and 8 $M_\odot$ with respect to the 4 $M_\odot$ stars.

As a test on the results presented in this Section, we also run several AGB models with a Reimers mass-loss (Reimers 1975) and different values of the Reimers parameter η ($\eta = 1$, 5, 10 for all masses and metallicities). We find that, even for the higher η values, the super-Li rich phase is reached with a mass-loss rate smaller than $\sim 5 \times 10^{-6}$ $M_\odot$ yr^{-1}. Therefore, the resulting ^{7}Li yields are very close to those obtained with the VW93 standard case (shown in the first three columns of Table 1). However, we stress that large variations in the parameter η may induce significant feedback on the AGB evolution, and the results of our synthetic models may not be completely reliable.

4.3. Galactic Li enrichment: HBB in 3 $M_\odot$ AGB stars with low Z?

It is commonly believed that HBB only occurs for masses greater than about 4 $M_\odot$. This is not strictly true: the temperature at the base of the envelope has also a strong dependence on the metallicity of the star. When the temperature at the base of the deep convective envelope is larger than $\sim 2 \times 10^7$ K, ^{7}Be is efficiently produced and the surface ^{7}Li abundance increases. For the models presented here, HBB occurs with initial masses ≥ 5 $M_\odot$ at each metallicities and ≥ 4 $M_\odot$ for $Z = 0.004$. In principle, at lower metallicities the inner envelope becomes hot enough to start HBB at lower masses, but models of lower metallicities through the AGB phase are rare.

Preliminary calculations for low values of Z have been presented by Lattanzio et al. (2001). They found that, for $Z = 0.0001$, envelope temperatures as high as $\sim 2 \times 10^7$ K are reached for masses as low as 2.5 $M_\odot$. Because of the shape of the IMF we would thus expect these stars to contribute substantially to ^{7}Li production, via HBB. In addition, as shown above, the maximum abundances obtained in the models discussed in this paper are $\log \epsilon(^7\text{Li}) \simeq 4$, independently on the stellar mass and metallicity. Therefore, under these preliminary indications, we tested the sensitivity of ^{7}Li enrichment when we extend the HBB mass range to 3–6 $M_\odot$ at low metallicities ($Z < 0.004$). For $M < 4$ $M_\odot$ we adopted the same yields of the 4 $M_\odot$ model presented above (detailed models are in preparation), and for $M \geq 4$ $M_\odot$ we used the yields obtained with VW93 increased by a factor of 50 (see Table 1 and discussion in the previous Section. The result for GCE of ^{7}Li is shown in the lower panel of Figure 6. There is a significant increase of the ^{7}Li enrichment mostly due to the higher weight of these stars on the IMF, as well as an important increase of the ^{7}Li contribution of these stars at the epoch of the solar system formation ($\sim 40\%$).

5. The production of ^{7}Li by novae

Novae can in principle contribute to the ^{7}Li enrichment of the ISM via the production and subsequent decay of ^{7}Be (i.e. Cameron-Fowler Beryllium mechanism). This process can be investigated in detail only with the help of hydrodynamical simulations of the accretion and explosive phases of evolution of a nova system. Early works by Arnould & Nørgaard (1975), Starrfield et al. (1978), Shara (1980), and Iben & Tutukov (1984) showed that ^{7}Li can be produced in considerable amounts during nova outbursts. Subsequent studies by Boffin et al. (1993) and Coc et al. (1995) pointed out the sensitivity of the results to the adopted nuclear reaction network and the treatment of convection between the accreted envelope and the underlying white dwarf core. A systematic analysis of the chemical composition of the ejecta of both CO and ONe novae has been recently presented by Hernanz et al. (1996) and José & Hernanz (1998, hereafter JH98) by means of hydrodynamical simulations following both the accretion and the explosion phase. Their results can be summarized as follows: (*i*) the production of ^{7}Be is weakly dependent (logarithmically) on the initial ^{3}He concentration in the envelope, for fractional abundances of ^{3}He larger than the solar value; (*ii*) the final ^{7}Li abundance depends rather sensitively on the chemical composition of the envelope, which, in turn, depends on the composition of the underlying core: typically, the ^{7}Li abundance by mass is in the range $\sim 10^{-6}$–10^{-5} in the case of a CO white dwarf, and $\sim 10^{-7}$–10^{-6} in the case of ONe white dwarfs; (*iii*) the predicted ejected mass during a nova outburst is $\sim 10^{-5}\ M_\odot$.

It should be stressed that the amount of mass ejected during a nova outburst predicted by hydrodynamical models ($\sim 10^{-5}\ M_\odot$) is systematically lower than the value observationally determined in a small sample of nova systems, peaked around $\sim 10^{-4}\ M_\odot$ (see e.g. Della Valle 2000 for a summary of results). However, the envelope masses inferred from observations are highly uncertain. In addition, the usual assumption that the ejected shells are almost homogeneously filled in (filling factor $\sim$ 0.1–1) has been challenged by recent observations of the Nova T Pyx (Shara et al. 1997), suggesting values of the filling factor in the range 10^{-2}–10^{-5}. Incomplete knowledge of the mass of nova ejecta is the most serious limitation to a quantitative evaluation of the role of novae as ^{7}Li sources in the Galaxy.

Crude estimates of the total amount of ^{7}Li synthesized by Galactic novae have been given by Starrfield et al. (1978), Hernanz et al. (1996), and JH98. They all consistently show that novae can account for $\sim 10\%$ of the Galactic ^{7}Li content. The contribution of novae to the Galactic evolution of ^{7}Li has been considered by D'Antona & Matteucci (1991), Matteucci et al. (1995), Romano et al. (1999), in the framework of models of Galactic chemical evolution. However, a detailed study of the role of novae as ^{7}Li producers necessarily suffers from several uncertainties. On one hand, the relevant quantity, i.e. the amount of ^{7}Li ejected into the ISM

during a nova outburst, is the product of two poorly constrained factors: the ^{7}Li abundance and the total mass ejected. On the other hand, the evaluation from first principles of the nova rate in the Galaxy requires the accurate knowledge of a number of physical processes and quantities which are neither theoretically nor observationally well determined, such as the white dwarf cooling timescale, the fraction of binary stars, and the fraction of binary stars that end up as a nova system.

In this Section, we estimate the *upper limit* to the amount of ^{7}Li synthesized by novae in the Galaxy, in particular deriving approximate analytical expressions for the abundance of ^{7}Li as a function of the gas metallicity. In the framework of the "closed box" model for the solar neighborhood (see e.g. Tinsley 1980), it is easy to predict the evolution of the ^{7}Li mass fraction $X_7(\mu)$ as a function of the gas fraction μ in the Galaxy. Let's define a *nova mass ejection rate* $\varphi_{\rm N}(t) = M_{\rm ej}\nu_{\rm N}(t)$ (in $M_\odot$ yr^{-1}), where $\nu_{\rm N}(t)$ is the nova rate (in yr^{-1}), and assume that the rate of mass ejection by novae is proportional to the star formation rate, $\varphi_{\rm N}(t) = \alpha\psi(t)$, with α independent of time. Indicating with $\langle X_7\rangle_{\rm ej}$ the average mass fraction of ^{7}Li in nova ejecta, and $X_{7\rm in}$ the initial (cosmological) ^{7}Li abundance, we obtain

$$X_7(\mu) = X_{7\rm in}\mu^{R/(1-R)} + \frac{\alpha\langle X_7\rangle_{\rm ej}}{R}[1-\mu^{R/(1-R)}], \tag{4}$$

where $R \simeq 0.21$ according to Galli et al. (1995) is the *stellar returned fraction* over the Galactic lifetime. The first term in eq. (4) represents the ^{7}Li destruction by astration, the second term the ^{7}Li production by novae. It is convenient to eliminate the gas fraction μ in favour of the metallicity of the gas Z, given by

$$Z(\mu) = -\frac{P_Z}{1-R}\ln\mu, \tag{5}$$

where $P_Z \simeq 7.9\times10^{-3}$ (Galli et al. 1995) is the *metal production factor.*

Notice that the contribution of novae to the evolution of ^{7}Li in the Galaxy depends almost linearly, at late times, on the combination $\alpha\langle X_7\rangle_{\rm N}$. The value of α, being constant, can be estimated at the present time $t = t_{\rm Gal}$,

$$\alpha = \frac{M_{\rm ej}\nu_{\rm N}(t_{\rm Gal})}{\psi(t_{\rm Gal})} \simeq 2\times10^{-4}\left(\frac{M_{\rm ej}}{3\times10^{-5}\ M_\odot}\right)\left(\frac{\nu_{\rm N}(t_{\rm Gal})}{35\ {\rm yr}^{-1}}\right)\left(\frac{\psi(t_{\rm Gal})}{5\ M_\odot\ {\rm yr}^{-1}}\right)^{-1}, \tag{6}$$

where we have adopted the value of the nova rate recently proposed by Shafter (1997) and the star formation rate given by Metzger (1988). As for $M_{\rm ej}$ and $\langle X_7\rangle_{\rm ej}$ we have adopted the average values given by Romano et al. (1999) for $t > 4.5\times10^7$ yr, based on the results of JH98: $M_{\rm ej} \simeq 3\times10^{-5}\ M_\odot$ and $\langle X_7\rangle_{\rm ej} \simeq 3\times10^{-6}$. Clearly for $\alpha \sim 10^{-4}$ the role of novae in the Galactic evolution of ^{7}Li is marginal, the ^{7}Li abundance predicted by the simple model

at $t = t_\odot$ ($X_7 \simeq 1 \times 10^{-9}$) being only $\sim$ 10% of the meteoritic value ($X_{7\odot} \simeq 9.3 \times 10^{-9}$). This result is in agreement with the order-of-magnitude estimates by Starrfield et al. (1978), Hernanz et al. (1996), and JH98.

Several approximations have been made in the derivation of the results of this Section. However, they are likely to lead to an overestimate of the predicted ^{7}Li abundance. Consider for instance the assumption of Instantaneous Recycling Approximation (IRA) for novae. Owing to the long evolutionary timescales necessary to produce a nova system, the ratio α was considerably smaller in the past (see D'Antona & Matteucci 1991, Romano et al. 1999), and the approximation of a nova rate proportional to the SFR, with the proportionality constant α estimated at the present time, results in an overestimate of the past nova rate and therefore the ^{7}Li abundance. Neglecting infall also results in an overestimate of the ^{7}Li abundance predicted by the model, if the infalling material has primordial composition and therefore acts as a diluting effect on the disk ^{7}Li abundance. The same is true neglecting the delay of about $\sim$ 1 Gyr estimated by D'Antona & Matteucci (1991) between the onset of star formation in the Galaxy and the birth of the first nova system.

Finally, another independent argument against a *dominant* contribution of novae to the production of ^{7}Li is the constraint on the abundance of isotopes like ^{13}C, ^{15}N and ^{17}O produced copiously by novae according to JH98. The constraint that we discuss below is independent of any specific model of chemical evolution. In Table 2 we show the average mass fraction of these isotopes in nova ejecta, assuming the yields computed by JH98 for CO and ONe novae (third and fifth column), together with their abundances in the protosolar material (first column), representative of the ISM composition at $t = t_\odot$ (from Anders & Grevesse 1989, and Grevesse, Noels & Sauval 1996). In the fourth and sixth column we show the contribution of novae to the solar abundance of each element *assuming that novae are*

TABLE 2

PRODUCTION OF ^{13}C, ^{15}N, ^{17}O, AND ^{7}LI BY NOVAE

	$X_\odot$	$\langle X\rangle_{\rm ej}$ (a)		$\langle X\rangle_{\rm ej}$ (b)	
^{13}C	3.6×10^{-5}	1.0×10^{-1}	100% (assumed)	2.4×10^{-2}	100% (assumed)
^{15}N	3.6×10^{-6}	1.5×10^{-2}	150%	5.3×10^{-2}	220%
^{17}O	3.4×10^{-6}	1.1×10^{-2}	120%	3.0×10^{-2}	130%
^{7}Li	9.3×10^{-9}	3.0×10^{-6}	**12%**	9.2×10^{-7}	**14%**

(a) CO novae (JH98 models)
(b) ONe novae (JH98 models)

the only producers of ^{13}C. This is obviously not the case, since it is well known that low- and intermediate-mass stars produce significant amounts of this isotope (see e.g. Palla et al. 2000 and references therein). We see from Table 2 that even under this favourable assumption on the role of novae in the chemical enrichment of the Galaxy, their contribution to the solar Li abundance cannot be greater than $\sim 10\%$.

6. The production of Li by SNII

Woosley et al. (1990) and Woosley & Weaver (1995, hereafter WW95) advanced the idea that production of ^{7}Li via the so called *neutrino process* in SNII could account entirely for the Solar System ^{7}Li abundance. Timmes, Woosley, & Weaver (1995), using a full grid of SNII models of various masses and metallicities, predicted a lower ^{7}Li production rate by the ν-process than Woosley et al. (1990), concluding that SNII contribute about one-half the solar ^{7}Li abundance (see also Matteucci et al. 1995 on this point).

With our model of GCE, assuming the ^{7}Li yields of WW95, we obtain the results shown in Figure 7. Starting with an initial ^{7}Li composition of $X_{7\mathrm{in}} = 1.0 \times 10^{-10}$, we found that SNII can account for $\sim 40\%$ of the meteoritic ^{7}Li content, in agreement with Timmes et al. (1995), and Matteucci et al. (1995). In order to show the exact value of the metallicity at which SNII in our GCE model start to contribute significantly, we also show in Fig. 7 the contribution of SNII computed with initial $X_{7\mathrm{in}} = 0$.

We should notice, however, that the SNII Li yields computed by WW95 have been questioned in recent theoretical studies of hydrodynamics and rotation in SNII (see e.g. Langer et al. 1999, and Heger, Langer, & Woosley 2000). In particular, Langer et al. (1999) showed that the inclusion of rotational mixing of the envelope of massive MS stars (later supposed to end as SNII) drastically reduces the amount of ^{3}He present in the stellar interior. In non-rotating massive stars this isotope is found to be neither produced nor destroyed. As shown by Langer et al. (1999) for a 15 $M_\odot$ rotating model, ^{3}He production factor is 0.1% of the correspondent case in a non-rotating WW95 model. Since ^{7}Li is largely produced by the ^{3}He$(\alpha,\gamma)^7$Li reaction, the inclusion of rotation in massive star models is expected to drastically reduce the production of ^{7}Li , with respect to the non-rotating cases. Thus, the results shown in Fig. 7 should be considered as upper limits for the contribution of SNII to the ^{7}Li enrichment in the Galaxy.

7. The production of ^{7}Li by deep mixing in low-mass giants stars

Pop. I low mass giant stars ($M < 4\ M_\odot$) are thought to produce Li both in the RGB and AGB phases. More specifically, low mass stars, below 2.5 $M_\odot$, produce ^{7}Li in the RGB and in the AGB by a deep mixing process such as explored by Wasserburg, Boothroyd, & Sackmann 1995, and Sackmann & Boothroyd 1999, hereafter SB99. This process is sometimes called cool bottom processing. We prefer to refer to this as "deep mixing" because it is more indicative of the physics involved: the cool bottom of the envelope does not play any role. The nuclear processing occurs at the top of the H-shell and this is facilitated by mixing from the bottom of the convective envelope down to the deeper layers of the H-shell. This mechanism needs to be further explored to see if it can be efficient also in the mass range $2.5 < M/M_\odot < 4.0$.

According to stellar evolution models, RGB stars should be characterized by a relatively low ^{7}Li content: stars that leave the MS undepleted in ^{7}Li , after the first-dredge up dilution has occurred, are expected to have ^{7}Li abundances of the order of $\log\epsilon(^7\mathrm{Li})\ \sim 1.5 - 1.9$ (Iben 1965, 1967a,b). Since most stars destroy ^{7}Li on the MS, their ^{7}Li content when they reach the RGB and in immediately subsequent phases should be much lower than the above values. Most field and cluster RGB stars show in fact very low ^{7}Li abundances ($-1.5 < \log\epsilon(^7\mathrm{Li}) < 0$), even lower than predicted by the models. An extra–mixing mechanism has been proposed to explain those low abundances (see e.g. Charbonnel, Brown, & Wallerstein 1998; Charbonnel & Balachandran 2000, and references therein). However, after the first discovery by Wallerstein & Sneden (1982) of a Li-rich RGB (i.e. a RGB star with a ^{7}Li abundance higher than model predictions), several other Li-rich giants have been found (for recent surveys, see Castilho et al. 1998; Jasniewicz et al. 1999). Note that, although the number of presently known Li-rich RGB stars is relatively high, they represent only 1–2 % of all the giants with ^{7}Li measurements (Wallerstein & Sneden 1982; Gratton & D'Antona 1989; Pilachowski, Hudek, & Sneden 1990; Pallavicini et al. 1990; Fekel & Balachandran 1993). Some of these Li-rich RGB stars have abundances even higher than the present ISM value (de la Reza & da Silva 1995; Balachandran 2000).

Various suggestions have been made to explain the Li-rich giants with $\log\epsilon(^7\mathrm{Li}) \geq 2$ (for stars with $1 < \log\epsilon(^7\mathrm{Li}) < 2$ a fresh ^{7}Li production is not necessary since their ^{7}Li abundance is consistent with the first dredge-up values). The high ^{7}Li content of these giants may be related to external processes (Alexander 1967; Gratton & D'Antona 1989; Siess & Livio 1999) or to internal processes such as the production of fresh ^{7}Li (Fekel & Balachandran 1993; de la Reza, Drake, & da Silva 1996; SB99). As shown by SB99, ^{7}Li can be created in low-mass RGB stars via the Cameron-Fowler mechanism associated with a deep-mixing below the convective envelope. This internal circulation (possibly driven by stellar rotation) transports envelope

material into the outer wing of the H-burning shell, where it undergoes partial nuclear processing, and then back to the envelope. SB99 choosed the free parameters of their model to match the low value of ^{12}C/^{13}C observed in RGB stars. In order to produce the required additional ^{13}C, the advected material must reach temperatures high enough that ^{3}He is burned, resulting in the creation of ^{7}Be via ^{3}He(α,γ)^{7}Be. If extra-mixing is slow, ^{7}Be is destroyed via ^{7}Be(p,γ)^{8}B(e^{+},ν)^{8}Be or ^{7}B(e^{-},ν)^{7}Li, and any ^{7}Li produced from ^{7}Be electron captures is immediately burned up via ^{7}Li(p,α)^{4}He. However, for higher mixing speed ^{7}Be can be transported out to cooler regions before electron capture takes place and the stellar envelope becomes enriched in ^{7}Li . The production of ^{7}Li in RGB stars is dependent on the mixing-speed, i.e. the stream mass flow rate. SB99 discussed the range of values of this mixing-speed and argued that it must be slower than the velocity of convection in RGB or AGB ($\sim 1\ M_{\odot}\ \mathrm{yr}^{-1}$), while the streams must move faster than the speed with which the H-shell burns its way outward. We show in Table 3 how the different values for the mixing-speed can influence the ^{7}Li production (see also SB99 for more details on the 1 $M_{\odot}$ model). It is important to notice that, as discussed by e.g. Charbonnel (1994) and Boothroyd & Sackmann (1999), the mass range in which the deep mixing is active is $\sim$ 1.0–2.5 $M_{\odot}$. This is due to the fact that for low mass stars ($\leq 2.5\ M_{\odot}$), the H-burning shell catches up to and erases the discontinuity while the star is still on the RGB; for higher masses ($> 2.5\ M_{\odot}$) the star leaves the RGB before this can take place.

We use the models by SB99 to estimate the contribution of low-mass RGB stars to the chemical evolution of the Galaxy. The ^{7}Li production phase on the RGB is short ($\sim 10^{5}$ yr) compared to the total red giant lifetime ($\sim 5 \times 10^{7}$ yr), and since the typical RGB mass-loss rate is rather low, they are not expected to contribute significantly to the ^{7}Li enrichment in the ISM. On the other hand, during the TP-AGB phase, because of the higher mass-loss rate, the contribution to the ^{7}Li ISM enrichment can be substantial. For these reasons, and since SB99 do not present specific ^{7}Li predictions for the AGB phase, in this work we make the following assumptions. We consider the SB99 ^{7}Li predictions at the end of the RGB phase (when $\log(L/L_{\odot}) \simeq 3.4$) for 1 $M_{\odot}$ at two different metallicities ($Z = Z_{\odot}$ and $Z = 0.001$) and for three different cases of mixing-speed (10^{-5}, 10^{-4}, 10^{-3} $M_{\odot}$ yr^{-1}). To obtain the yield of ^{7}Li from these models we multiply the ^{7}Li abundances by the total mass ejected, e.g. for 1 $M_{\odot}$ model we used $M_{\rm ej} \simeq 0.45\ M_{\odot}$ (see e.g. Weidemann 1984 for the initial-final mass relationship). We assume a mass range of 1–2.5 $M_{\odot}$, in agreement with the above discussion, and since the authors showed only the results for the 1 $M_{\odot}$ model, we interpolate the ^{7}Li production by deep mixing in the mass range 1 $M_{\odot}$ – 2.5 $M_{\odot}$. To derive the 2.5 $M_{\odot}$ ^{7}Li yields we follow SB99 assuming that all ^{3}He is converted in ^{7}Li , and that the abundance of ^{3}He in stars scales as M^{-2} (Schatzman 1987). The ^{7}Li yields obtained for 1 $M_{\odot}$ and 2.5 $M_{\odot}$, with different metallicities and different mixing speed, are shown in

Table 3. In our calculations, in order to derive an upper limit to the ^{7}Li production, we adopt the highest ^{7}Li abundance predicted by the SB99 models, i.e. that obtained with the model with 10^{-5} $M_\odot$ yr^{-1} mixing speed.

The contribution of low-mass giant stars to the Galactic evolution of ^{7}Li is shown in Figure 8. These stars enrich ^{7}Li up to $X_7 \sim 2.2 \times 10^{-9}$ at the epoch of formation of the Sun, i.e. $\sim 24\%$ of the solar value. Again, another more efficient source is required to explain the ISM ^{7}Li abundance. As in the case of SNII (Fig. 7) we show for comparison the contribution from these stars to ^{7}Li enrichment starting with a zero initial ^{7}Li composition.

8. Conclusions

We have addressed the long-standing problem of the Galactic chemical evolution of ^{7}Li with the aim of clarifying the role of the different stellar contributions. We have analyzed four possible stellar sources of ^{7}Li : SNII, novae, low-mass giants and IMS-AGB stars. For low-mass giants, novae, and SNII we have critically examined the available ^{7}Li yields and discussed the possible extrapolations when no model predictions were available. In the case of SNII and novae we re-examined the ^{7}Li yields in the light of recent hydrodynamical computations. For IMS-AGB stars we presented and used here new results for nucleosynthesis calculations based on evolutionary AGB models by Frost (1997). In particular, we discussed how the interplay between the HBB process and a phase of high mass-loss before the evolution off the AGB may constitute a key process for ^{7}Li enrichment in the Galaxy. Although we are not yet able to quantify the contribution of IMS-AGB stars, we have explored different realistic possibilities in terms of mass-loss rate and mass range for the HBB process.

The work presented here is summarized in Figure 9, where we compare the results of our model of chemical evolution with the sample of observational data presented in Fig. 1. The predicted ^{7}Li abundance resulting from all stellar sources considered in this paper is plotted in Fig. 9 vs. metallicity (upper panel) and vs. time (lower panel). For IMS-AGB we used a VW93 mass-loss increased by a factor of 50 (as discussed in § 4.2), and we have also taken into account the results obtained for the 3 $M_\odot$ AGB model presented in § 4.3.

As we discussed in Sect. 2.1, we also ran our model with an initial ^{7}Li abundance higher by a factor 2 than the Spite plateau value. The result is shown for comparison in Fig. 9. Notice that the predicted ^{7}Li abundance at the time of formation of the Sun is virtually the same in both cases. In the lower panel of Fig. 9 we plot the individual contributions from the different stellar sources, with the exception of the contribution from SNII since

we believe that the inclusion of rotation and mixing in the supernova models leads to a drastic reduction of the ^{7}Li yields (see § 6). Note that, from an observational point of view, it is critical to determine the metallicity where the rise of the ^{7}Li abundance from the Spite plateau occurs; the available data indicate that the rise from the plateau occurs at metallicities [Fe/H] between $\simeq -1$ and -0.8, but additional data in the metallicity range $-1 <$ [Fe/H] < -0.3 are needed in order to better constrain this value.

Our main conclusions are the following:

(*i*) In the light of the available stellar models, small contributions to the meteoritic ^{7}Li abundance come from novae ($\sim 10\%$ or less, see § 5) and low-mass giant stars ($\sim 20\%$, see § 7). As for SNII, we predict a contribution to the solar system ^{7}Li abundance of $\sim 40\%$ with the standard yields by Woosley & Weaver (1995), and a contribution less than 10% if the results of the latest hydrodynamical simulations of the supernova explosion are taken into account (see § 6). Spallation reactions between ISM and cosmic-ray nuclei can provide an additional at least $\sim$ 10–20% of the ^{7}Li abundance in the solar system (see e.g. Lemoine et al. 1998).

(*ii*) Figure 9 shows that even with our best-fit model we are not able to reproduce the meteoritic abundance, although both cluster and ISM abundances are fitted fairly well. Our best-fit model is in good agreement with the observed $\log \epsilon(^7\mathrm{Li})$ vs. [Fe/H] distribution up to [Fe/H] $\simeq -0.4$. This indicates that the metallicity at which the rise from the Spite plateau occurs is consistent with the [Fe/H] values at which the IMS-AGB stars contribute to the chemical enrichment of the ISM. We remind that the observational data for [Fe/H] > -0.4 are mostly taken from Balachandran (1990) (see discussion in § 2); nevertheless, as the comparison between photometric and spectroscopic metallicities shows, part of these stars might have higher [Fe/H] values.

(*iii*) Our best-fit model and, more specifically, the contribution from IMS-AGB, is based on two major assumptions: first the high mass-loss phase at the end of the evolution of these stars must start *earlier* on the AGB than the standard predictions by VW93. This is supported by recent IR observations, discussed in § 4. Second, we also need a contribution to ^{7}Li through HBB production from stars with $3\ M_\odot \leq M \leq 4\ M_\odot$ and low metallicities (see preliminary model results for $M < 4\ M_\odot$ in Lattanzio et al. 2001). Should these two assumptions be not valid, the contribution from intermediate-mass AGB would be much lower. We stress however that, since neither novae, nor SNII, nor low-mass giant stars seem to produce enough ^{7}Li to account for the present-day abundance, we believe that intermediate-mass AGB stars remain at present the best candidates as ^{7}Li factories.

Our results and conclusions are strongly based on the AGB models discussed in § 4

(see also Frost 1997). A different view has been recently expressed by Ventura et al. (2000). They presented a grid of IMS-AGB models of different masses and tested the sensitivity of ^{7}Li yields to different mass-loss rate prescriptions on the basis of a comparison with AGB stars in the Magellanic Clouds. Ventura et al. (2000) concluded that, with their mass-loss calibration, IMS-AGB stars do not contribute significantly to the ^{7}Li enrichment of the ISM. As they properly noticed, details of ^{7}Li production depend on the input parameters of the stellar model, mainly the treatment of convection. In addition, Ventura et al. (2000) focused their work on the analysis of the strength of the mass-loss rate during the AGB phase. We instead followed a different approach, testing different times during the AGB phase at which the high mass-loss rate starts, and looking for the consequences on ^{7}Li yields. As we demonstrated in § 4, anticipating by few thermal pulses the beginning of the superwind phase can have significant impact in the mass of ^{7}Li ejected.

Work in progress includes an extension of the grid of AGB models to lower masses ($M < 4\ M_\odot$) and lower metallicities ($Z < 0.004$) (see preliminary results in Lattanzio et al. 2001), in order to analyze the possibility of ^{7}Li production via HBB in these stars. Another interesting point that we just mentioned in this paper, is a re-analysis of the contribution of GCR to the production of ^{7}Li (Valle et al., in preparation). Finally, new ^{7}Li data for a statistically significant sample of stars in the critical metallicity range $-1 <$ [Fe/H] < -0.3 are being analyzed; the data will provide stringent observational constraints on the Galactic ^{7}Li abundance in a metallicity range where IMS-AGB stars are expected, on the basis of this work, to give their main contribution.

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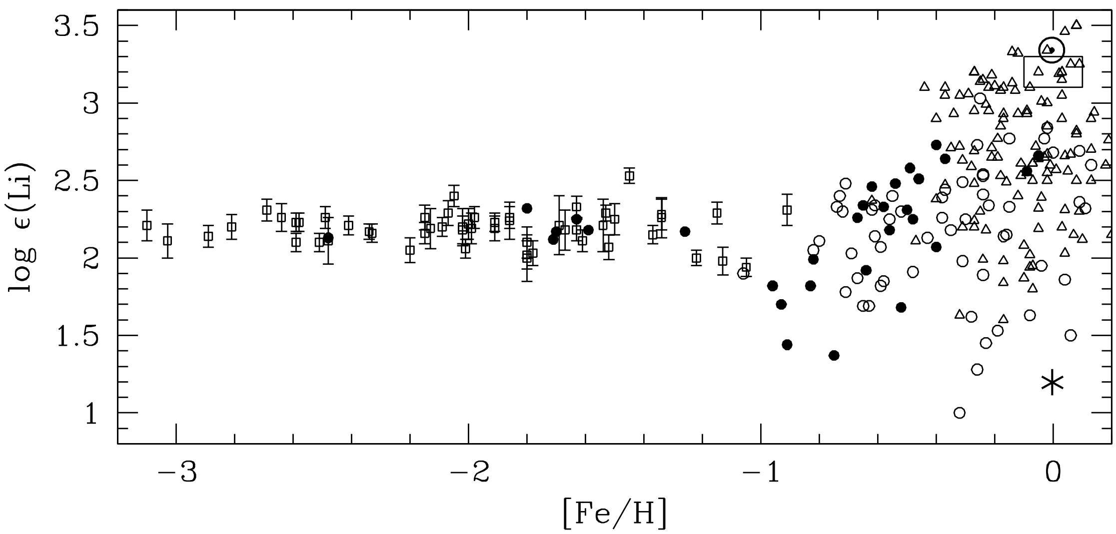
TABLE 3

^{7}LI YIELDS (IN SOLAR MASSES) BY DEEP MIXING IN LOW-MASS GIANT STARS

M ($M_{\odot}$)	mixing speed ($M_{\odot}$ yr^{-1})	$Z = Z_{\odot}$	$Z = 0.001$
1.0 $^{(a)}$	10^{-3}	3.8×10^{-10}	5.1×10^{-10}
	10^{-4}	2.0×10^{-9}	7.6×10^{-10}
	10^{-5}	1.0×10^{-8}	3.6×10^{-10}
2.5 $^{(b)}$	10^{-3}	2.1×10^{-10}	3.0×10^{-10}
	10^{-4}	7.6×10^{-10}	6.7×10^{-10}
	10^{-5}	6.0×10^{-9}	2.1×10^{-9}

(a) SB99 models.

(b) Our extrapolations from (a).



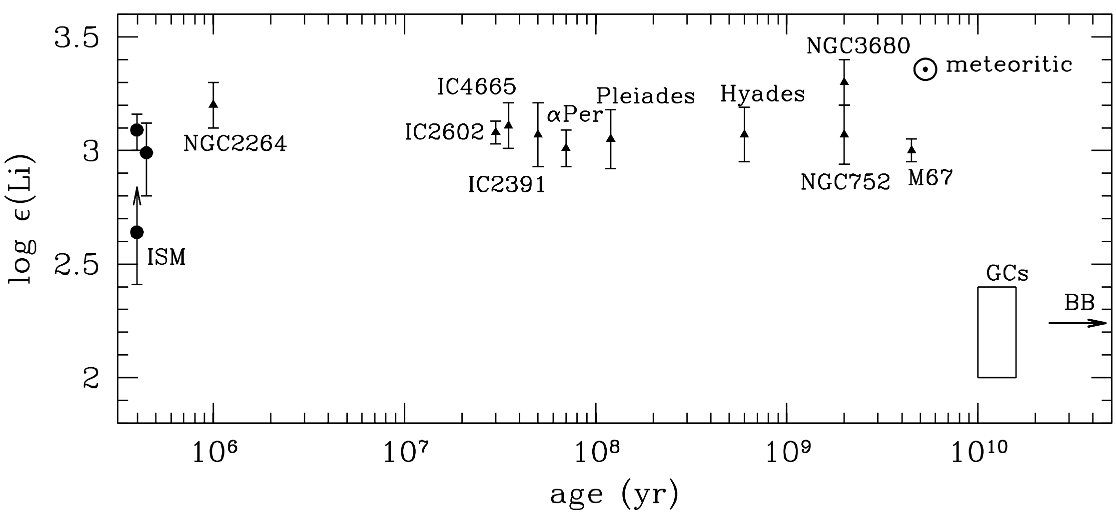


Fig. 1.— *Upper panel*: $\log \epsilon(^7\text{Li})$ vs. [Fe/H] for field stars. Observations are from Fullbright (2000) (*filled circles*), Bonifacio & Molaro (1997) (*open squares*), Balachandran (1990) (*open triangles*), Lambert et al. (1991) (*open circles*). The box represents the region occupied by stars in open clusters with undepleted ^{7}Li . The meteoritic and the (solar) photospheric values are also shown by a *dotted circle* and an *asterisk*, respectively. *Lower panel*: $\log \epsilon(^7\text{Li})$ vs. age for Galactic open clusters (*filled triangles*), and globular clusters (*box*). We also include different measurements of the ISM value (*filled circles*), the meteoritic value (*dotted circle*), and the cosmological ^{7}Li abundance adopted in this work (see text for references).

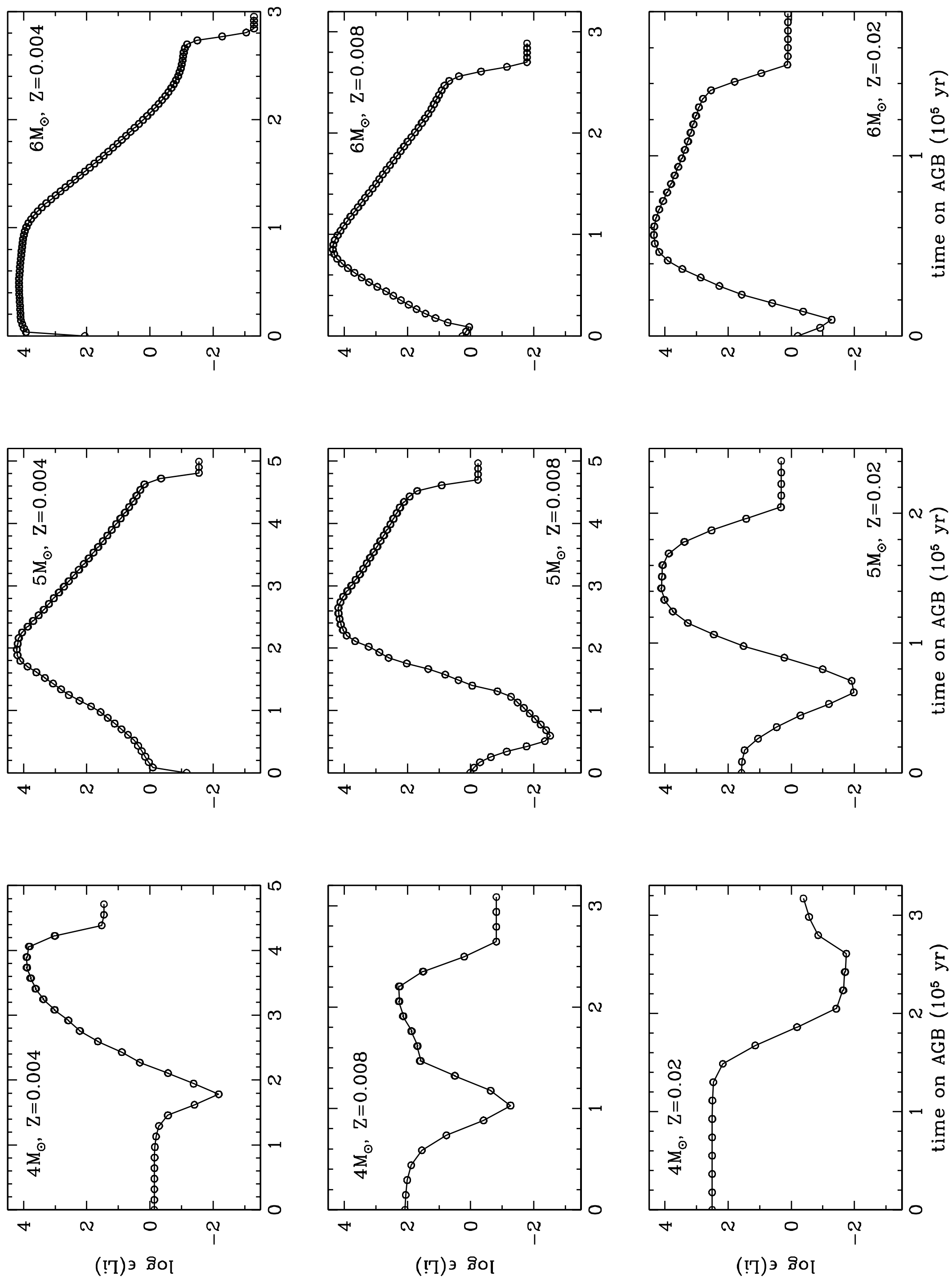


Fig. 2.— Surface ^{7}Li abundance in the envelope of 4, 5, 6 $M_\odot$ stars with $Z = 0.004$, 0.008, 0.02, vs. time on the AGB. Each circle represents a thermal pulse in the model.

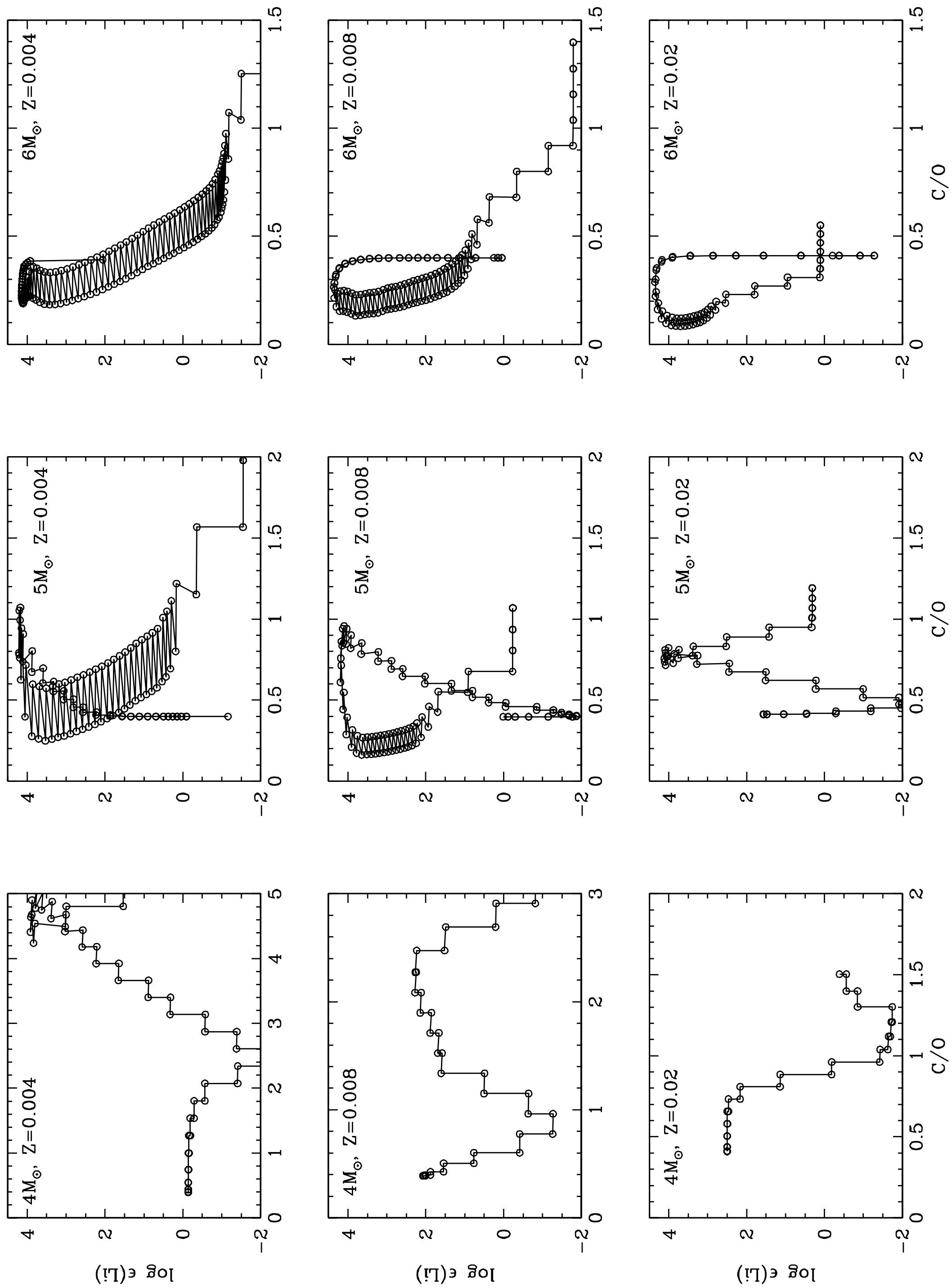


Fig. 3.— Surface C/O ratios vs. ^{7}Li surface abundances for the nine AGB models described in the text. Symbols are as Fig. 2.

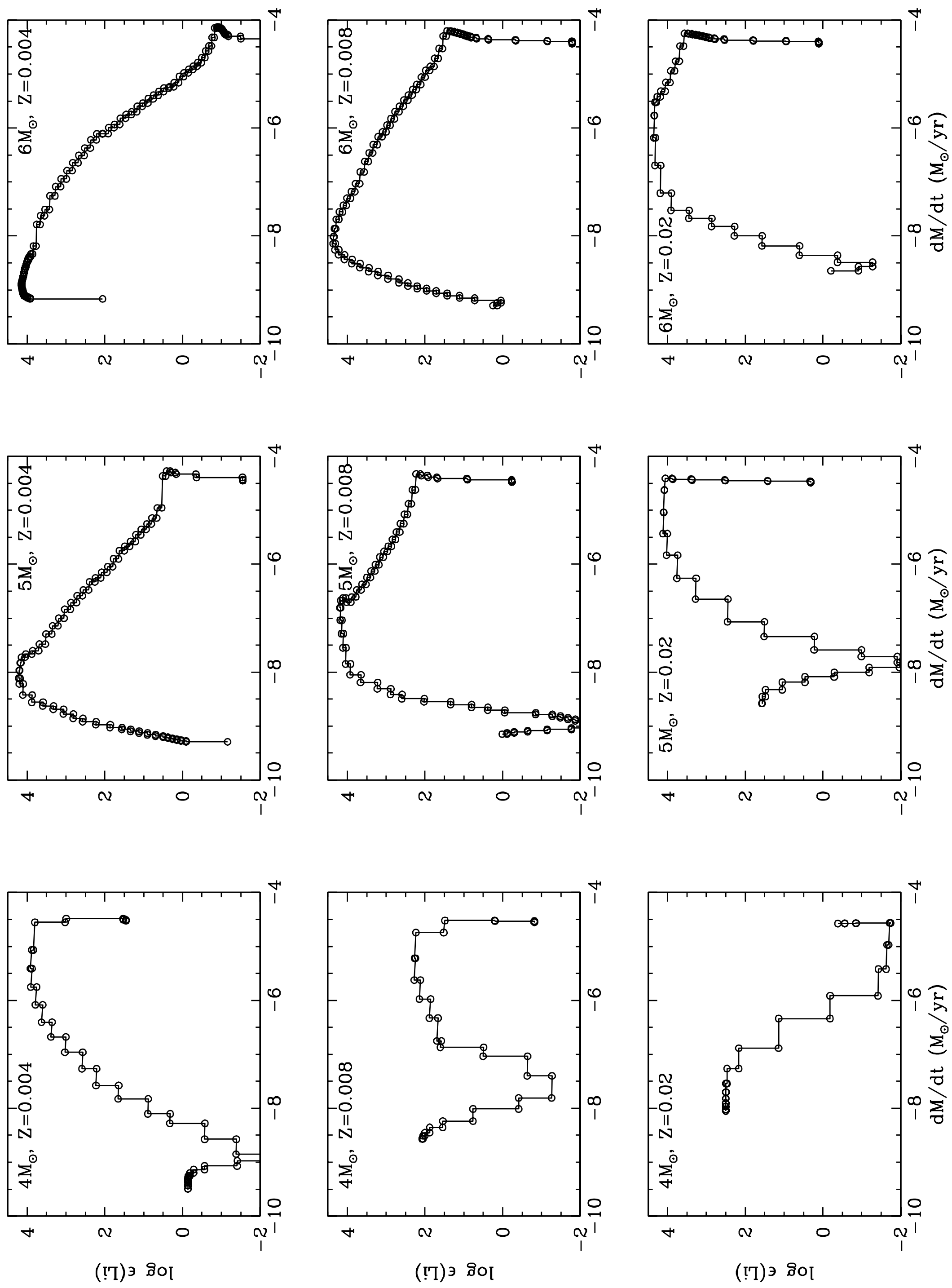


Fig. 4.— Surface ^{7}Li abundance vs mass-loss rate (in $M_\odot$ yr^{-1}) for the nine AGB models described in the text, following the mass-loss prescriptions of Vassiliadis & Wood (1993). Symbols are as Fig. 2.

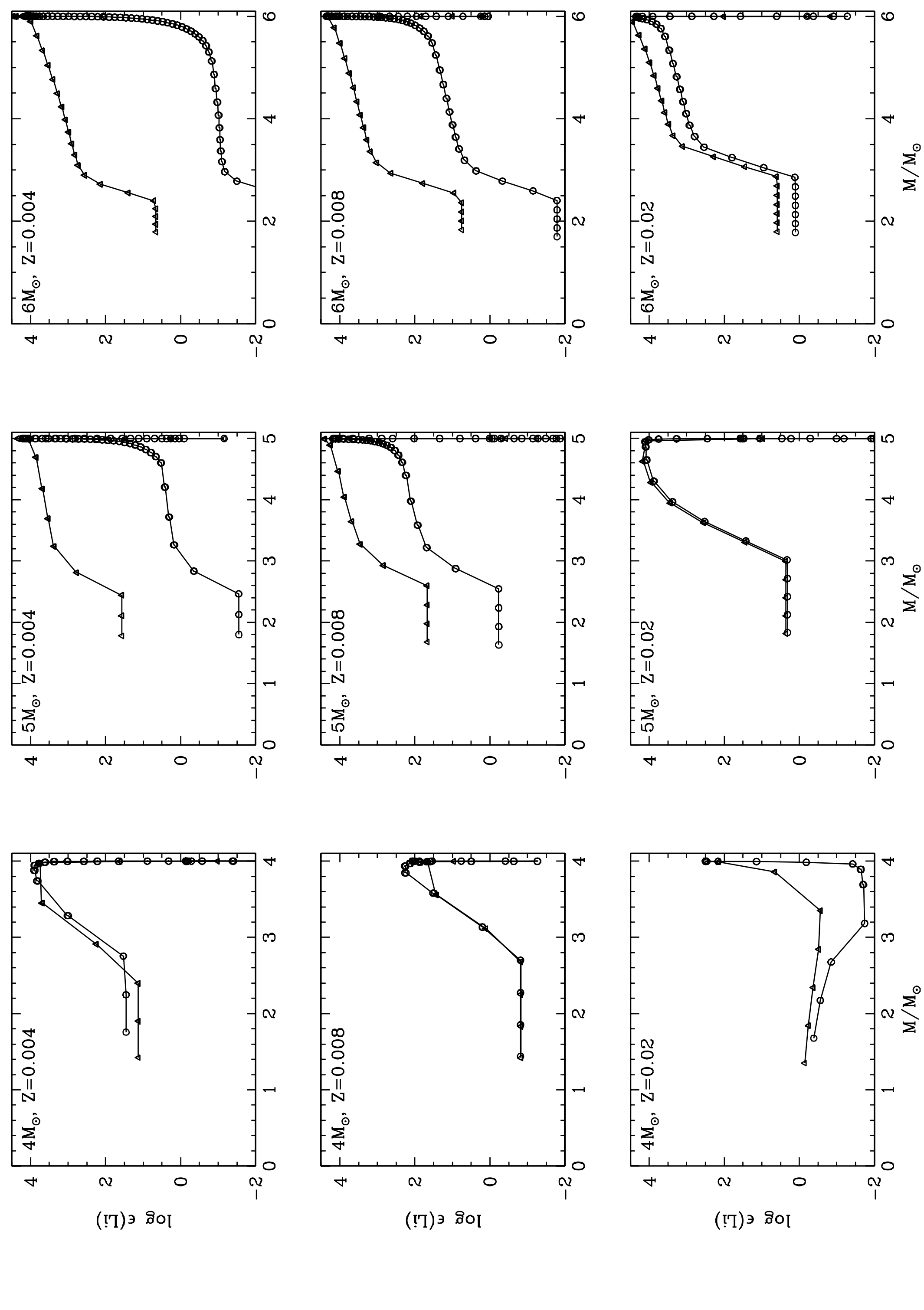


Fig. 5.— Surface ^{7}Li abundance vs. stellar mass for the AGB models discussed in the text. The *open circles* are for the Vassiliadis & Wood (1993) mass-loss, the *open triangles* are for the Vassiliadis & Wood (1993) mass-loss increased by a factor 50. Each open circle and open triangle represents a thermal pulse.

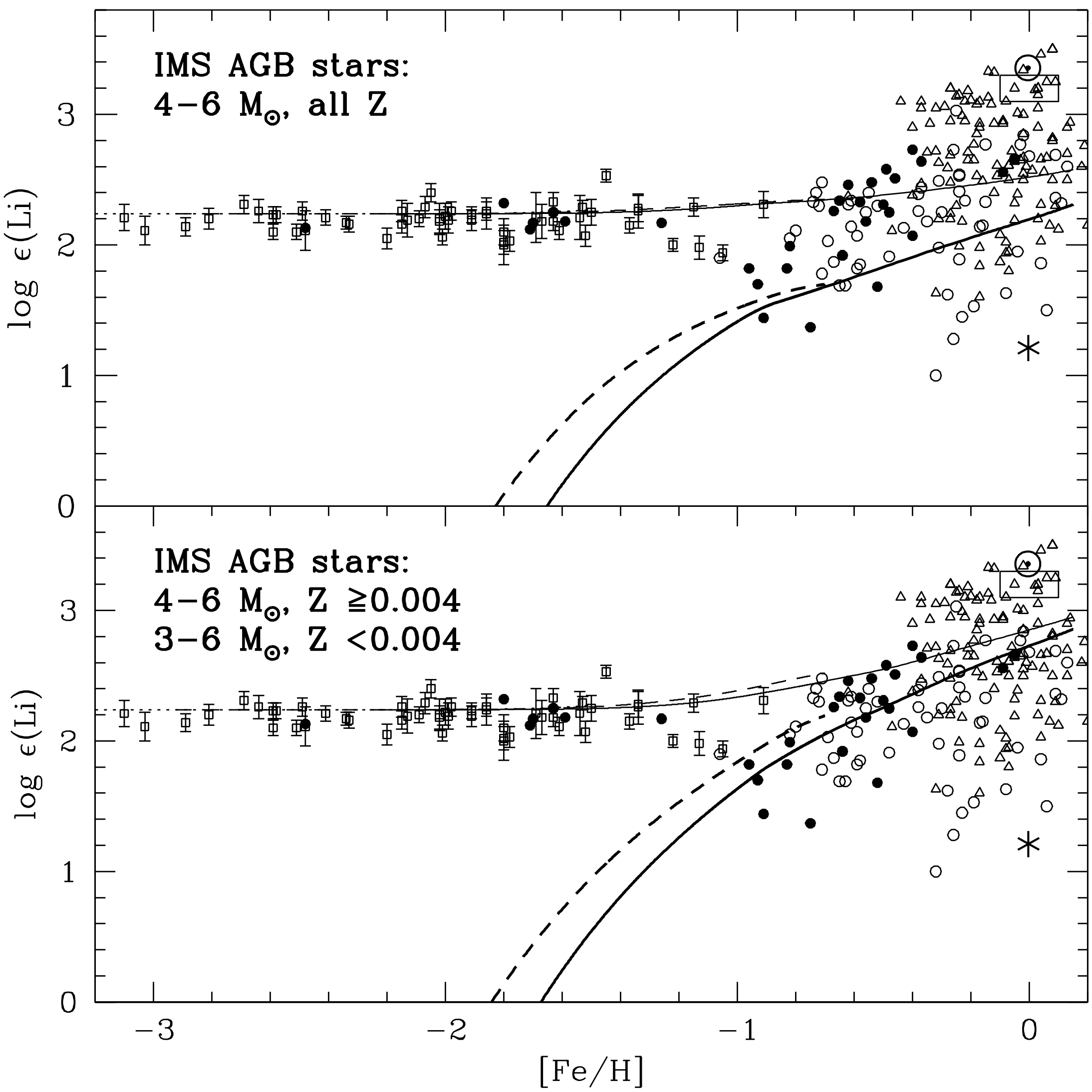


Fig. 6.— Contribution of IMS-AGB stars to the Galactic evolution of ^{7}Li , for two different choices of the IMS-AGB mass range: 4–6 $M_\odot$ (*upper panel*), and 4–6 $M_\odot$ for $Z \geq 0.004$ and 3–6 $M_\odot$ with $Z < 0.004$ (*lower panel*) (see also text for details). In both cases we adopt the mass-loss rate prescription of Vassiliadis & Wood (1993) with modification (see text). Symbols are as in Fig.1 (upper panel). Lines refer to the GCE model results for halo (*dotted*), thick disk (*dashed*), and thin disk (*solid*). Thick lines show the ^{7}Li evolution obtained with a zero initial abundance of ^{7}Li , to emphasize the contribution of IMS-AGB stars in the thick disk (*dashed line*) and in the thin disk (*solid line*).

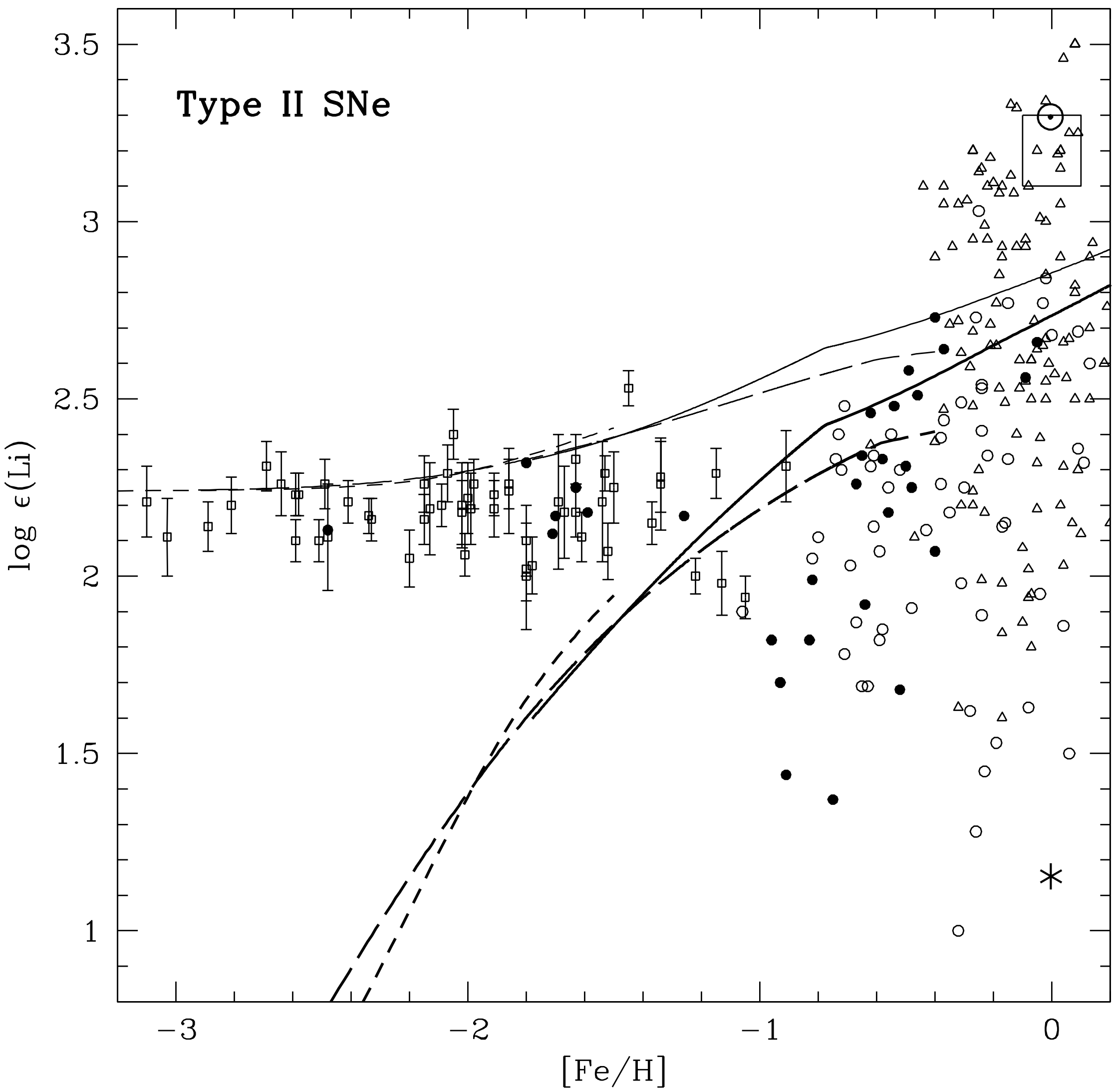


Fig. 7.— Contribution of SNII to the Galactic evolution of ^{7}Li (line types are as in Fig. 6). Thick lines show the ^{7}Li evolution obtained with a zero initial abundance of ^{7}Li , to emphasize the contribution of SNII in the thick disk (*dashed line*) and in the thin disk (*solid line*). Symbols are as in Fig.1 (upper panel).

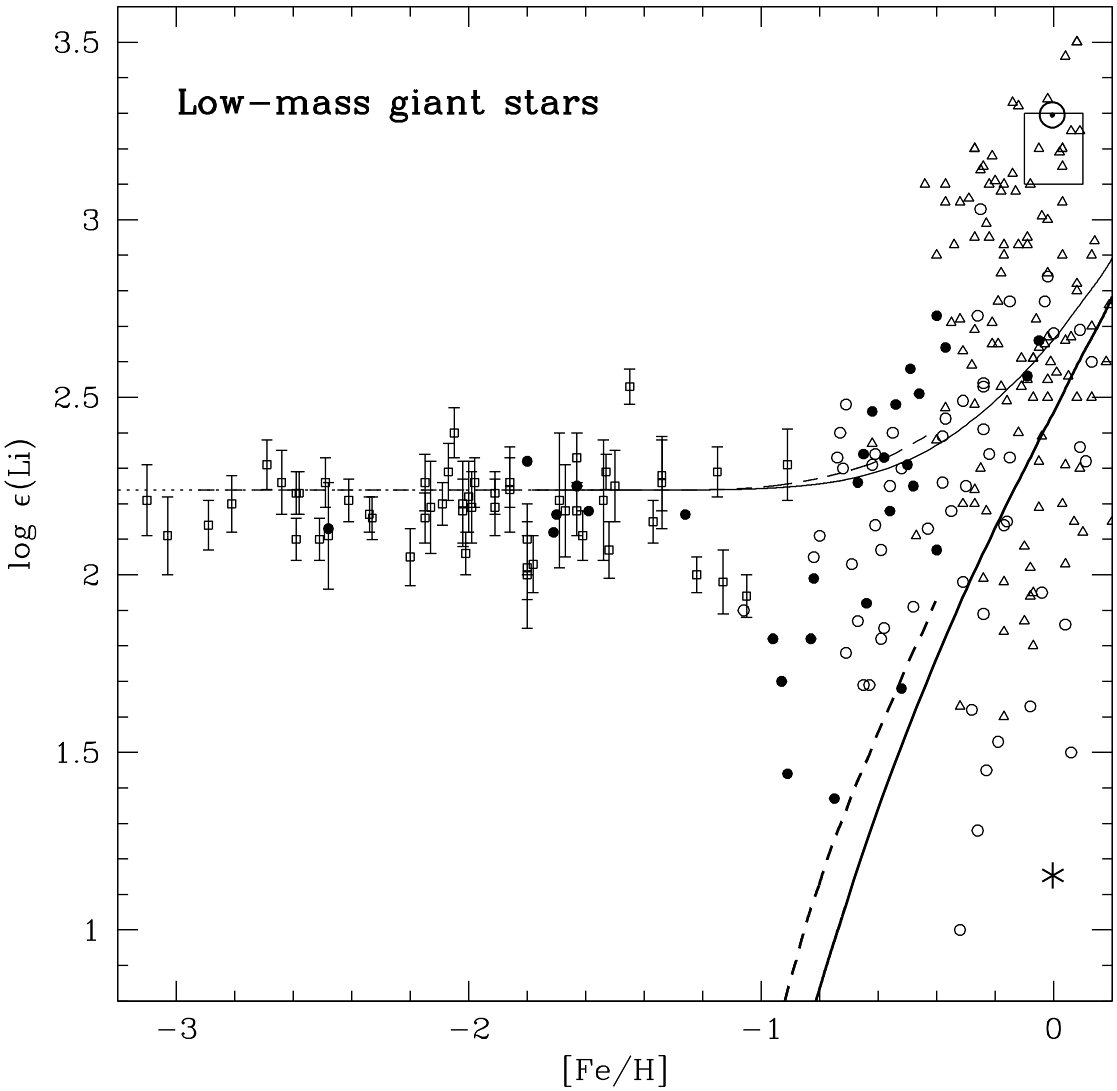


Fig. 8.— Contribution of low-mass giant stars via deep mixing process to the Galactic evolution of ^{7}Li (line types are as in Fig. 6). Thick lines show the ^{7}Li evolution obtained with a zero initial abundance of ^{7}Li , to emphasize the contribution of low-mass giants in the thick disk (*dashed line*) and in the thin disk (*solid line*) Symbols are as in Fig.1 (upper panel).

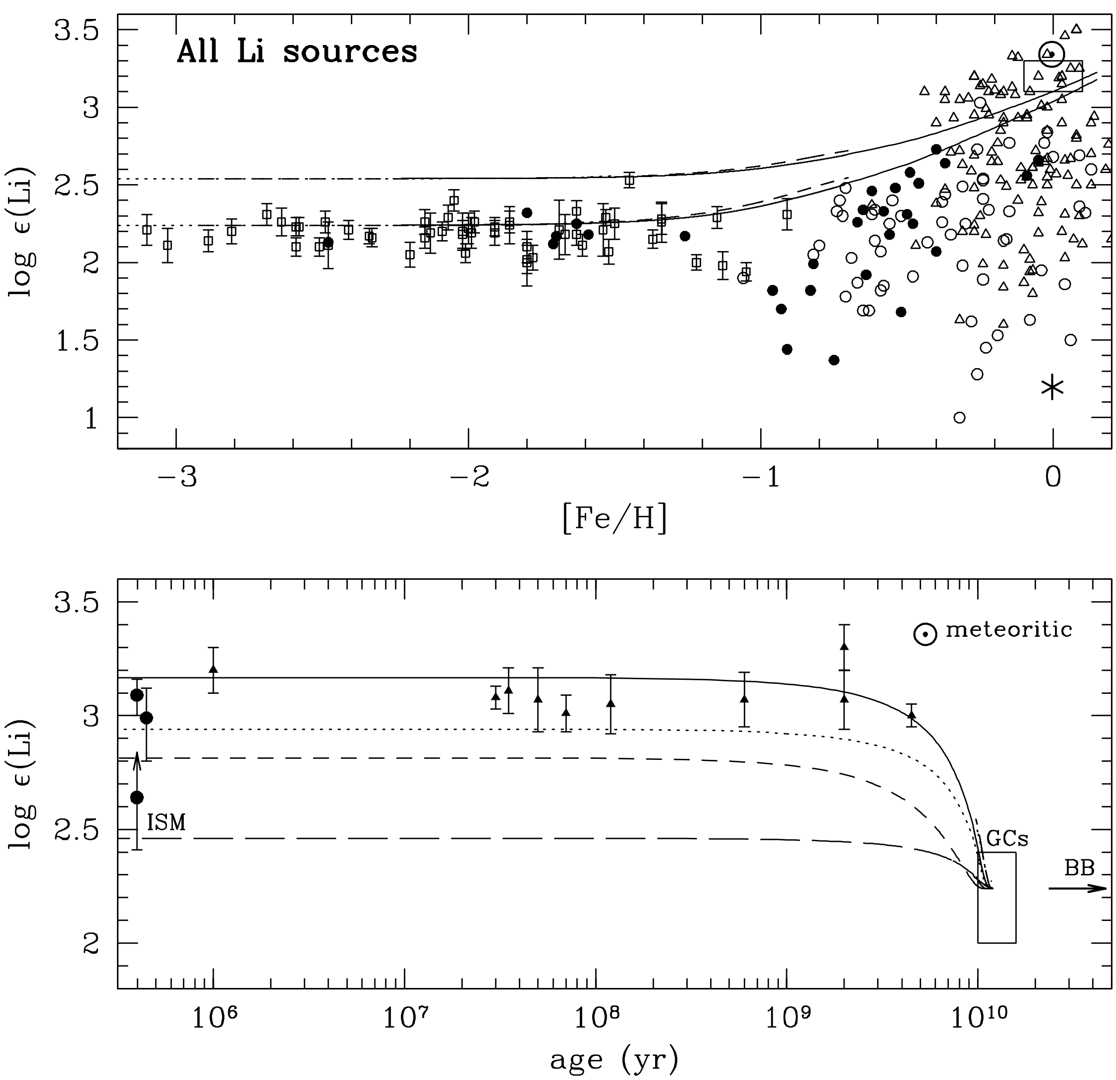


Fig. 9.— *Upper panel*: evolution of ^{7}Li as a function of [Fe/H] according to our model taking into account the contribution of novae, low-mass giants and IMS-AGB stars (line types are as in Fig. 6). We also show the results obtained starting with an initial ^{7}Li abundance higher by a factor 2 than the Spite plateau. *Lower panel*: $\log \epsilon(^7\mathrm{Li})$ vs. age for Galactic open clusters (*filled triangles*) and globular clusters (same symbols as in Fig. 1). We indicate the individual contributions of novae (*long-dashed line*), low-mass giants (*short-dashed line*), and IMS-AGB stars (*dotted line*). The *solid line* shows the total contribution from all sources considered.